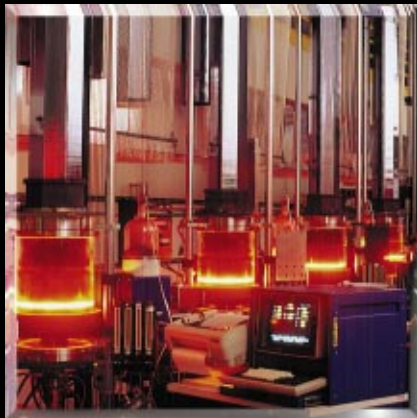
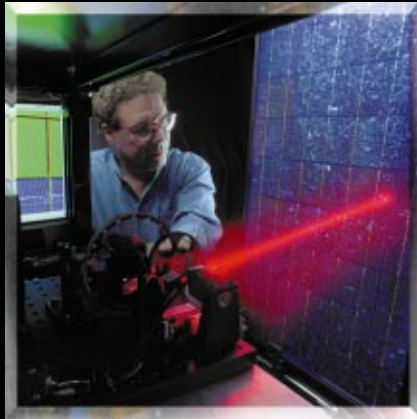


# PHOTOVOLTAICS

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# Our Mission

Our mission is to make photovoltaics (PV) a significant part of the domestic economy—as an industry and an energy resource. More than two decades of research and development (R&D), in partnership with industry, has advanced PV from a laboratory novelty to today's growing U.S. industry, which grossed more than \$350 million in 1995.

With further R&D, photovoltaics will contribute much more to the national economy. Reducing system costs from about \$7 per watt to \$3 per watt could result in a domestic industry with billions of dollars in annual sales. A recent market study by the Utility PhotoVoltaic Group estimated a potential domestic market for PV of 9000 megawatts at a system price of \$3 per watt. Photovoltaics has enormous potential as a cost-competitive source of electricity because reducing costs to below \$3 per watt is also possible.

We face a number of challenges to reduce the cost of electricity generated by PV systems and to increase their efficiency and lifetime. Working together, researchers in the national laboratories, the nation's universities, and industry—the three major participants in the National Photovoltaics Program—are prepared to meet these challenges.

We will meet them with a well-balanced national program, with key milestones in both basic research and technology applications. The program includes world-class R&D to maintain U.S. leadership in technical breakthroughs and extensive work with industry to reduce manufacturing costs and to improve systems. The program also includes projects that validate today's prototype systems in applications throughout the world.

This 5-year plan for the National Photovoltaics Program outlines initiatives such as the Thin-Film PV Partnership, new phases of the PV Manufacturing Technology (PVMaT) Program, and Utility PhotoVoltaic Group projects for system validation. It also provides for cooperative international activities with the World Bank, the Global Environmental Facility, and applications in Asia, South and Central America, Africa, Eastern Europe, and the republics of the former Soviet Union.

Our discussions with industry and utility leaders help us recognize that, to make PV a significant part of our economy, we must develop technology for specific applications. As PV system costs decline, the range of system uses will expand from today's high-value consumer products and remote applications to grid-connected building systems, grid-distribution support, utility peaking power, and bulk power applications.

To accelerate the use of PV in broader applications, we have established goals that serve as benchmarks for the progress we expect. Achieving these goals is necessary to make PV an important contributor to the U.S. economy. As in previous program plans, we outline here the work required to meet these strategic objectives.

The Department of Energy's (DOE's) own strategic plan focuses on five areas: energy resource development, science and technology, industrial competitiveness, national security, and environmental quality. They provide a framework for a commitment at the highest levels to the goals and principles of the National Photovoltaics Program. Because of this commitment within DOE, and our strong partnerships with industry, the outlook is promising for reaching the goals of this 5-year plan.

Achieving those goals will bring us significantly closer to the 9000-megawatt market projected by the Utility PhotoVoltaic Group. Expanding our efforts to include closer collaboration with utilities, industry, universities, other government agencies, and international organizations will help leverage our resources for maximum benefit to the nation.

James E. Rannels, Director  
Photovoltaics Technology Division  
U.S. Department of Energy  
Washington, D.C.







*Bringing electricity to the world—a woman in India collects potable water provided by a PV-powered pump.*

Harin Ullal, NREL/PIX01993

# Executive Summary

The potential market for photovoltaics—the direct conversion of sunlight into electricity—is staggering. Since 1987 the worldwide demand for photovoltaics has grown from 29 megawatts per year to 84 megawatts per year, an increase of nearly 290%. During the same period, U.S. PV companies have increased their module shipments by 400% and have increased their share of the world PV market to 41%.

This is just the beginning for this versatile, promising new energy technology. Photovoltaics is finding increasing acceptance in remote and developing areas around the world, where some two billion people still lack the benefits of electricity. In the United States, applications for electricity generated by PV are rapidly expanding to new and larger markets.

The U.S. PV industry is poised to meet this national and international demand. And the U.S. Department of Energy's National Photovoltaics Program (hereafter also referred to as the PV Program or simply the program) is helping to make this attractive

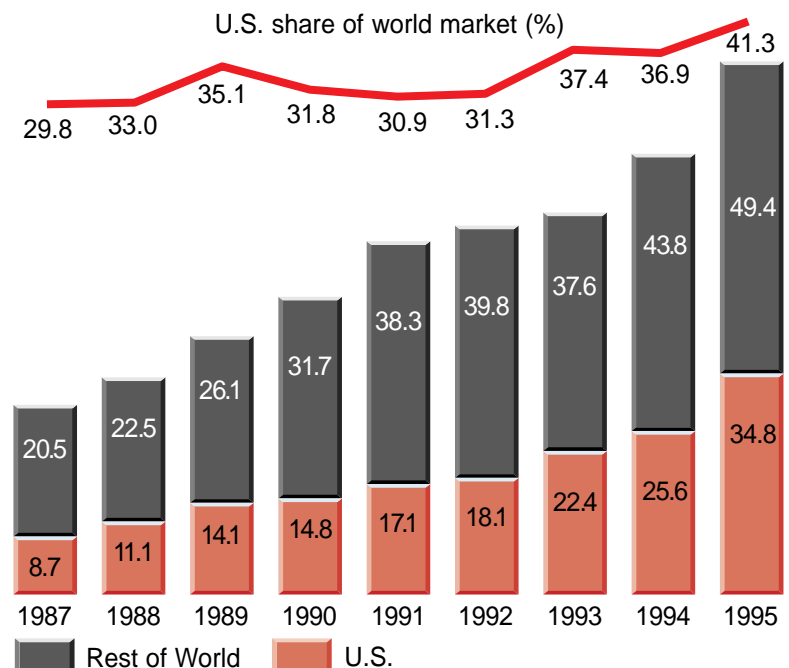
technology a significant part of the U.S. economy.

**T**he PV Promise. U.S. industry and the National Photovoltaics Program are investing their money, talent, and time in photovoltaics because of the energy, economic, and environmental benefits the technology holds for the nation and for the world.

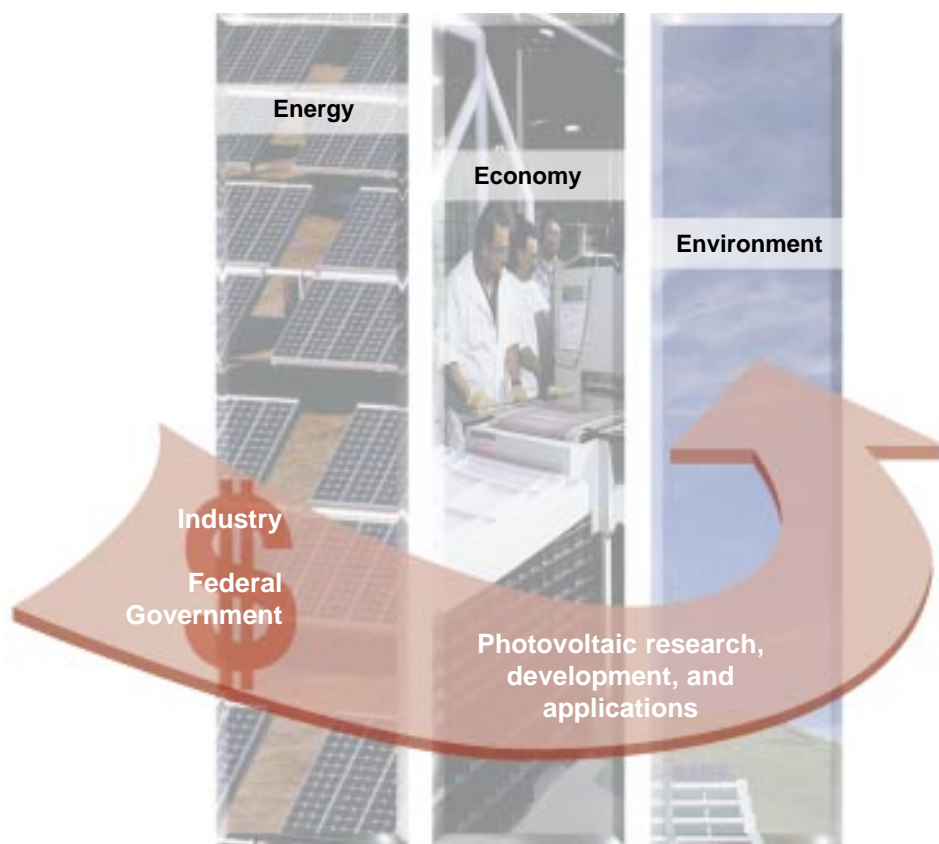
Photovoltaics is a versatile energy technology that can be used for almost any application requiring electricity, no matter how big or small and no matter how remote (see sidebar on page 6). It is increasingly becoming the preferred source of electricity for many applications. And it is a domestic technology that relies on a domestic resource—sunlight; as such, it reduces the nation's dependence on imported fossil fuels.

Photovoltaics is a high technology that, as a domestic industry, could create or support as many as 3800 well-paying jobs for every \$100 million worth

*Photovoltaics has enormous energy, economic, and environmental promise. To help meet this promise, the National Photovoltaics Program manages a wide-ranging and integrated approach in which it collaborates with U.S. industry and academia to make PV devices more efficient, to make PV systems more competitive, and to validate the technology.*



Since 1986, the U.S. has increased its module shipments by 400% and its world market share to 41% (sales in megawatts).



*Industry- and government-funded photovoltaic research and development promote the three E's: energy, economy, and the environment.*

of PV sales. Currently, the U.S. PV industry does more than \$350 million of business per year, has increased its manufacturing capacity to 35 megawatts per year, and has sold more than 210 megawatts of modules, cumulative. We expect this growth trend to continue, with cumulative sales surpassing 400 megawatts by the year 2000 and 10,000 megawatts by the year 2030. In fact, a study by the Utility PhotoVoltaic Group suggests that, as system costs drop to \$3 per watt, we may see demand rise to greater than 9000 megawatts; and this is for domestic applications alone. An additional benefit of PV for the U.S. economy derives from the fact that much of U.S. production (currently about 70%) is exported, which helps restore the balance of trade. This benefit will become even greater as the PV industry grows.

Photovoltaic systems have a low environmental impact. Because the operation of a PV system produces no air pollution, waste fuel products, or global warming gases, the widespread use of PV will produce a better domestic and global environment.

Moreover, generating electricity with sunlight is only one way to make use of photovoltaics. Our research is

revealing other potential uses for PV as well, such as converting waste heat into electricity through thermal photovoltaics and producing hydrogen as a nonpolluting fuel.

**T**he PV Challenge. For PV to meet its promise, both in terms of an energy technology and in terms of a domestic industry, we must do two major things.

First, we must ensure that the U.S. PV industry not only grows into a large domestic industry but also that it remains competitive in the world PV markets. This means we must maintain the technical superiority of our products. U.S. industry has been a leader in PV technology thanks to the ongoing support of the National Photovoltaics Program and the tenacity of the U.S. companies. To maintain this leadership, the program and the companies must continue their close collaboration.

Second, for PV to be seriously considered as a major energy option, we must expand old markets and enter new ones by making PV competitive in a wider variety of applications and with more forms of electrical generation.

To accomplish both of these aims we are presented with the technical challenge of continuing to reduce the cost of photovoltaic systems while making them more reliable, durable, and convenient to use. Although this has been the constant aim of the National Photovoltaics Program—since 1980 industry and the program have reduced the cost of PV-generated electricity to about 25 cents per kilowatt-hour and have increased module lifetimes to 20 years—continuing to do so will make photovoltaic systems as attractive to consumers as the next best alternative for a wide spectrum of electric power applications.

**M**eeting the Challenge. To meet the challenge before us, the National Photovoltaics Program uses a four-pronged strategy: First, we work in close concert with industry and other stakeholders to develop specific goals that serve as significant milestones on the path to achieving a PV technology competitive with other sources for generating electricity—in applications ranging from high-value consumer products, international and remote projects,

buildings, utility distribution, peaking power, and, finally, bulk power markets.

Second, we use a vertically integrated development process to bring technologies from the concept stage to commercial readiness. This process—which has feedback loops along the way—includes basic research, applied research, engineering, product development, and manufacturing refinements before it finally results in a new commercial product.

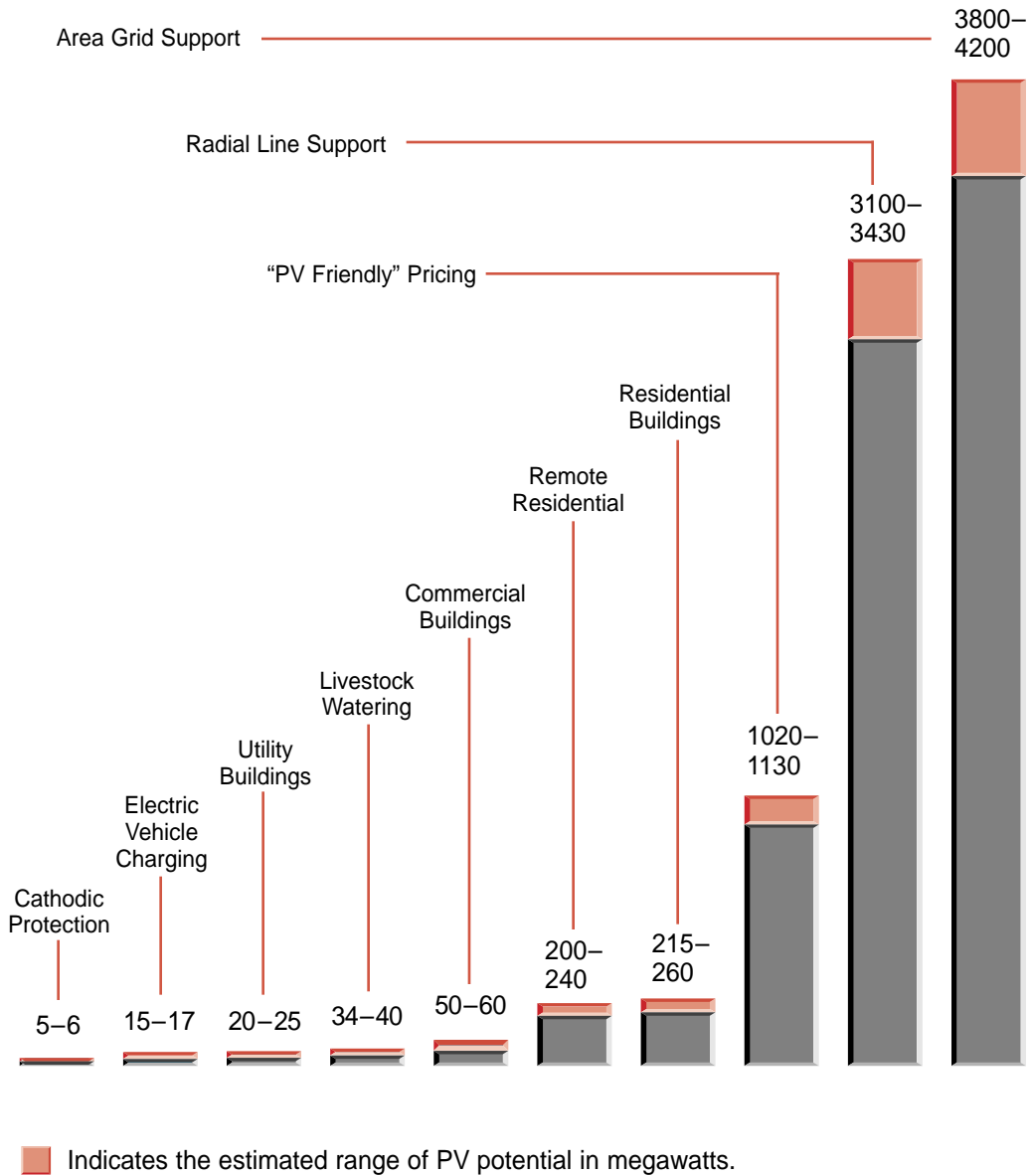
Third, all along this development process we collaborate closely with R&D partners from government, industry, and universities. This lends stability to the program and leverages the expertise, funds, and facilities of the partners.

Finally, we validate the technology for specific applications by deploying prototype systems and documenting their performance.

The success of this strategy depends on the expertise and contributions of the program's partners in the national laboratories, universities, and PV industry. The national laboratories provide long-term, high-risk, but high-payoff R&D. The laboratories' cutting-edge R&D breakthroughs continue to advance the performance and reliability of photovoltaic technologies. The technology transfer activities of the National Photovoltaics Program ensure that information reaches the private sector and provides opportunities for industry to collaborate with laboratory researchers. In collaborative projects, research engineers have developed more-efficient fabrication and manufacturing

processes, better encapsulants and module packaging, automated manufacturing systems, and refined balance-of-systems components. They have also helped to establish uniform standards and test methods, rigorous procedures for qualification testing of PV systems, and data bases of environmental, resource, and market information.

Through subcontracts, universities that participate in the National Photovoltaics Program play a key supporting role in almost every phase of technology development. Their expertise in fundamental science and materials and device research adds immeasurably to the foundations of



A recent study by the Utility PhotoVoltaic Group indicates a demand for 9000 megawatts of power at a system price of \$3 per watt in 10 domestic applications.



science, the advancement of the technology, and the effectiveness of the program.

And through collaborative interactions, industry provides feedback to researchers and engineers on products and processes. Industry gives the program guidance at all points along the development path. As an integral member of R&D efforts, industry often assumes the lead role in the engineering and product development phases of a technology's development. Therefore, in 1995, industry received more than 90% of program funding in technology development and more than 60% of the funding in systems engineering and applications. In the end, it is industry that brings all the efforts of the



*R&D: using a femtosecond laser to explore fundamental characteristics of PV materials.*

Jim Yost Photography/PX01623

National Photovoltaics Program to fruition in the form of lower-cost PV products.

**I**mplementing the Program. Critical to the success of this strategy is the National Photovoltaics Program's effort to reduce the cost of electricity generated by photovoltaics. The program is doing this in three primary ways: by making devices more efficient, by making PV systems less expensive, and by validating the technology through measurements, tests, and prototypes. We accomplish these tasks under the program's three main elements: research and

development, technology development, and systems engineering and applications.

## PV Applications

The list of actual and potential PV applications could include nearly anything that requires electric power.

**S**tand Alone. Photovoltaic systems can supply electricity in areas where there is no electric grid, or where connecting to that grid would be too expensive.

*Water pumping*—Thousands of PV-powered water pumps are installed worldwide each year, supplying water for households, light industry, agriculture, villages, and livestock. Photovoltaic systems can replace hand pumps or large engine-powered water-pumping systems, and PV is bringing fresh water to areas that never had wells before.

*Cathodic protection*—Each year, metal corrosion causes billions of dollars of damage to pipes, tanks, well heads, wharves, bridges, and buildings buried in earth or installed under water. Photovoltaic-generated electricity prevents electrolytic corrosion of such structures.

*Communications*—Today, PV systems are powering communication systems such as microwave repeaters, television and radio transmitters and receivers, telephone systems, and small radios in remote areas.

*Lighting and small appliances*—In some areas, where there is no electric power available, PV can be used to light single homes, operate a television, or power a street light. In the developing world, improving indoor lighting allows small industry to expand, while replacing kerosene lanterns improves indoor air quality. In the United States, PV panels and a battery power many small electrical devices from security lights to switches.

*Village power*—In the developing world there are hundreds of thousands of villages without electric power or that use diesel generators, which are expensive to fuel, difficult to maintain, and environmentally harmful. In the United States there are also communities or enterprises that operate on diesel-powered generators when PV could reduce operating costs and reduce environmental concerns. Photovoltaic village power systems provide electricity for any domestic,



*Research and development.* For photovoltaics to make a significant contribution to the nation's energy resource mix, the technology must be improved and electricity from photovoltaics must become more cost-competitive. Therefore, we continue to conduct basic and applied research on promising new materials, processes, devices, and production techniques. We also carefully measure, model, and evaluate new concepts. We perform these R&D activities in three primary areas: thin films, crystalline silicon, and advanced, high-efficiency concepts.

*Thin films.* The program investigates four thin-film materials—amorphous silicon, cadmium telluride, copper indium diselenide, and thin-layer crystalline silicon—because of their potential for low cost and high performance. As part of its investigations, the program has a major new initiative—the Thin-Film PV Partnership—under which it has awarded cost-shared contracts to nine industry technology partners and to about 20 university R&D partners to develop prototype products based on the four thin-film materials.

For amorphous silicon, the program explores ways in which to reach higher conversion efficiencies; to improve the design and fabrication of multijunction amorphous silicon alloy cells and modules; and to develop processing techniques, such as hot-wire deposition, to enhance both stability and efficiency.

Cadmium telluride devices can be manufactured with methods that potentially cost very little. But we still need to understand this material better, improve the efficiencies of devices made from it, achieve uniform stabilities, and transfer the results to pilot-scale manufacturing.

In 1995, copper indium diselenide achieved a thin-film record efficiency of 17.1% in the laboratory, but products using this material are not yet commercially available. Before we can successfully manufacture commercial devices made with copper indium diselenide we must understand phase-change reactions and the effects of temperature during fabrication. We must also simplify the production process and transfer new techniques to industry.

If constructed to trap light properly, devices made from thin-layer crystalline silicon can be more efficient than

community, or industrial activity, including operating computers. Photovoltaics can also be used with diesel generators, allowing them to run less often.

**G**rid-connected. Innovative uses of PV systems connected to the utility grid are being assessed to supply electricity when and where it will have the highest value.

*Demand-side management*—Because power plants brought on line to serve peak demand periods are usually the most expensive to operate, electricity generated by grid-connected PV systems at peak periods has the highest value. Utilities strive to smooth out electrical demand with a combination of incentives to customers called demand-side management. Photovoltaic systems on buildings would operate to reduce peak demand of the buildings. In combination with batteries, such systems could also reduce peak loads that occur after sunset. If such systems could be called upon or “dispatched” by the utility like other forms of generation they would have even greater value.

*Transmission and distribution support*—As electrical demand increases in portions of a utility

company's service territory, the transmission and distribution system may need to be expanded. This can be quite expensive, requiring new larger transformers and possibly larger distribution lines. Installing PV generation near substations or at the end of overloaded lines can eliminate or delay the need for costly upgrades. By helping the utility avoid expensive upgrading, the electricity generated by the PV system has greater value.

*Bulk power generation*—Large-scale generation of electric power is an important long-term application for photovoltaics. Although not cost-effective at today's PV system prices, the cooperative research of the National Photovoltaics Program aims to push down the cost of electricity generated by PV systems to the point of being competitive with other widely used forms of generation.

**O**ther. The list of actual and potential PV applications is large and growing larger. It includes vaccine refrigeration, consumer products, space power applications, pond aeration, electric-vehicle charging, and others too numerous to mention.

other thin-film devices. To achieve this aim, the program is exploring ways in which to make the material less than 50 micrometers thick, is researching a low-cost substrate and buffer layer, and is developing better light-trapping and interconnection schemes.

**Crystalline silicon.** Under the Crystalline Silicon Research Cooperative, the program explores methods with which to achieve higher efficiency devices made with less expensive, industrial-grade silicon. The program also investigates how material impurities reduce the efficiency of devices; this understanding will enable manufacturers to compensate for or avoid these defects.

**Advanced, high-efficiency concepts.** We develop advanced technologies for specialized markets, such as PV concentrator systems. These include highly efficient (32% goal in the near term), single- and multijunction devices based on gallium arsenide and related III-V alloy materials. Industry efforts in this area are driven by space markets today. The program also investigates thermophotovoltaic devices, which convert thermal radiation to electrical energy.

**Technology development.** To translate laboratory innovations into technical improvements for commercial products, the National Photovoltaics Program investigates three areas: manufacturing technology, module development, and balance-of-system (BOS) components.

**Manufacturing technology.** Through collaborations, industry and the National Photovoltaics Program have reduced module production costs by as much as 50% during the last 5 years, and hope to decrease them by another factor of 2 during the next 5 years. This they intend to do by increasing throughput; by modifying laboratory techniques for production; by assessing new manufacturing processes and finding better ways to scale up manufacturing processes; by measuring, analyzing, and characterizing PV materials and devices; and by simplifying PV systems and incorporating the most durable, cost-effective components possible.

Most of this work is performed under the auspices of the PVMaT (PV Manufacturing Technology) initiative.

It addresses manufacturing R&D for crystalline silicon, concentrators, and various thin-film technology options.

**Module development.** Through measurements, analysis, accelerated testing, and collaborative R&D, the

National Photovoltaics Program intends to produce better, stronger encapsulants and to improve the performance, durability, and lifetime of photovoltaic modules.

**Balance-of-system components.** Although balance-of-system components, such as inverters, batteries, support structures, junction boxes, and control systems represent just half the cost of PV systems, they are responsible for as much as 99% of system failure and repair problems. The goal here is to increase the efficiency of these components, increase their reliability through optimized designs, and reduce their costs

through mass production.

**Systems engineering and applications.** To help industry improve the performance, reliability, and operational characteristics of its products, the National Photovoltaics Program tests and evaluates the material, mechanical, electrical, and safety characteristics of cells, modules, BOS components, and complete systems. Under this program element, the new outdoor test facility at the National Renewable Energy Laboratory (NREL) will support program activities with numerous test results of prototype and precommercial modules.

To help products become accepted in potential markets, the PV Program helps industry and standards groups develop national and international safety and reliability standards appropriate for PV products.

To validate prototype PV technologies, the program deploys systems in stand-alone and utility-tied domestic and international applications and measures and analyzes their performance. These projects help demonstrate the most cost-effective PV applications for key markets.

For domestic applications, the program works closely with groups of users—such as the National Parks Service, Forest Service, military agencies, and utilities—who represent large markets for PV systems.



*Technology development: addressing manufacturing R&D through the PVMaT initiative.*

ASE Americas/PIX01561

For international applications, the program has pilot projects in several nations and works with agencies from these nations, international lending agencies, specific system users, and nongovernment organizations.

The majority of the work under this program element involves crystalline silicon photovoltaics, although the activities will benefit future thin-film PV technologies.

**G**uiding the Effort. In one sense, this collaborative program is guided by representatives of all its participants in national laboratories, industry, and universities. More specifically, PV Program managers in DOE's Office of Energy Efficiency and Renewable Energy, and in the national laboratories, develop comprehensive operating plans based on strategic, multiyear plans such as this one, which respond to the broad policies for energy R&D determined by the Executive and legislative branches of the federal government.

Through sound management practices and continual fine-tuning, program managers ensure that the budget allocations, direction, and individual elements of the

National Photovoltaics Program meet the objectives of the nation and stay on target. Individual project and research managers at the national laboratories and DOE's field offices administer both in-house research and cost-shared R&D

contracts with the private sector. Federal funding for the PV Program was nearly \$75 million in FY 1994 and \$84 million in FY 1995. Industrial partners typically cost-share the contract research efforts, 50-50, in the program. In addition, private-sector investments in developing manufacturing facilities exceed the government investment in R&D by a factor of 2 or more. Other investments and new financing are also crucial to our success. Large national and multinational projects require the participation of international development and financing organizations.

Future program-sponsored R&D activities will continue to

explore new and better ways to convert sunlight to electricity and to assist promising young industries in becoming self-sustaining. The promise of photovoltaics will be fulfilled when this versatile, operationally simple technology is fully able to meet a significant share of the needs of our nation—and the entire world—for clean, affordable electricity.



*Systems engineering and applications: deploying and evaluating systems in a variety of applications.*

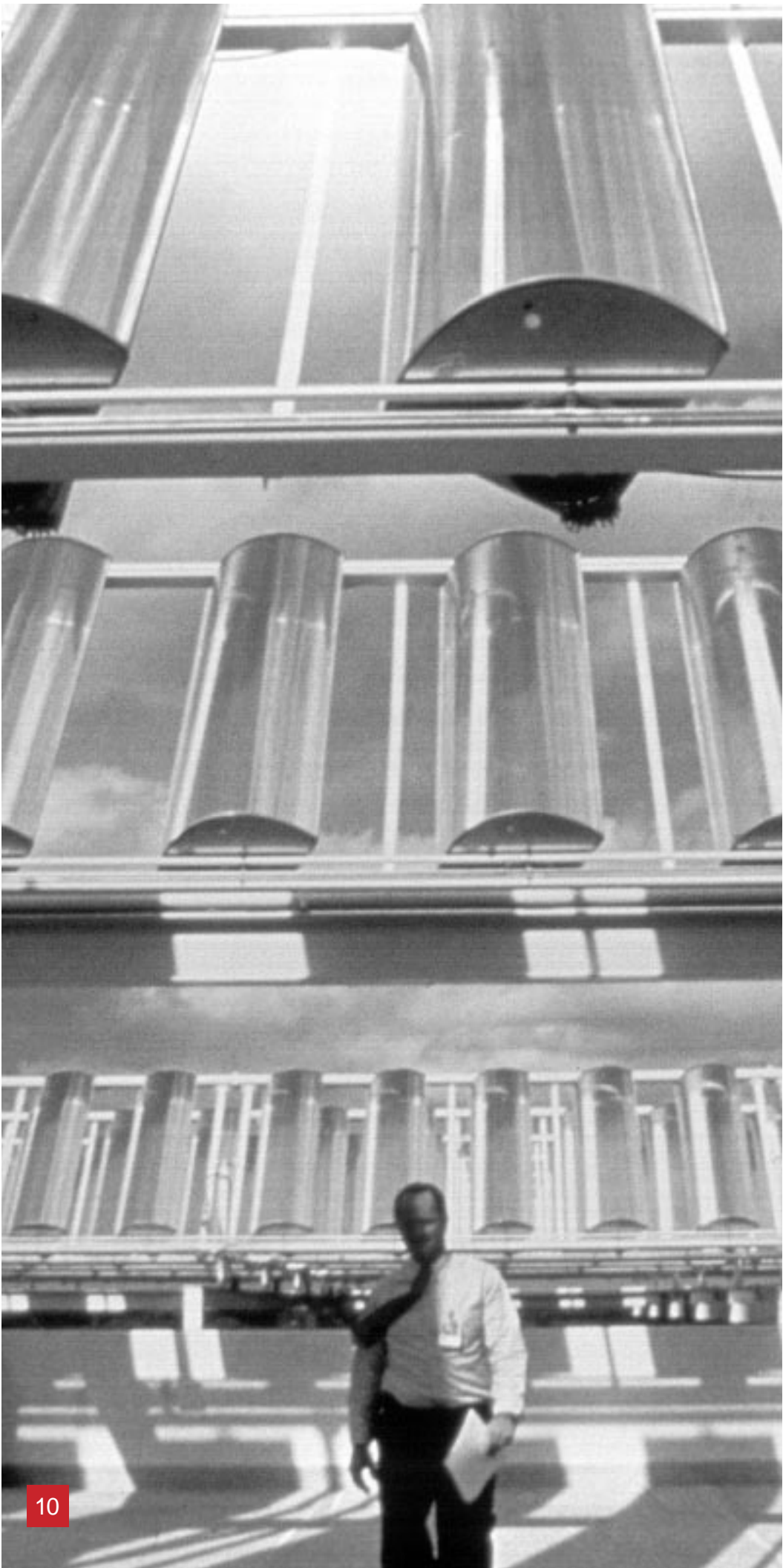
Solar Electric Light Fund/PIX01543

	1991	1995	2000	2010–2030
Electricity price (¢/kWh)	40–75	25–50	12–20	<6
Module efficiency* (%)	5–14	7–17	10–20	15–25
System cost (\$/W)	10–20	7–15	3–7	1–1.50
System lifetime (years)	5–10	10–20	>20	>30
U.S. cumulative sales (MW)	75	175	400–600	>10,000

\*Range of efficiencies for commercial flat-plate and concentrator technologies.

*Photovoltaic progress and program goals (costs and prices in 1995 dollars)*





*In Austin, Texas, a 300-kilo-watt concentrator system supplies part of the power for the 3M Company's research center.*

3M Company/PIX00014

# The PV Promise

The potential of PV goes well beyond its versatility as an energy technology. Photovoltaics also holds great economic and environmental promise.

As an energy technology, photovoltaics can be used for almost anything that requires electricity—from small, remote applications to large central power stations. This is not only a versatile technology that gives our nation a wide range of choices for generating electricity, it is also a home-grown technology that depends only on sunlight for fuel and domestic materials for construction.

Photovoltaics is also an emerging technology that will help our nation's economy grow. There are already thousands of PV systems in use across the nation. And the Utility PhotoVoltaic Group estimates that, as system costs drop below \$3 per watt, we may see the domestic demand rise to greater than 9000 megawatts. This would make PV a multibillion dollar industry generating thousands of well-paying jobs.

The international market may have an even larger potential. Today, with its share of the photovoltaic market having grown to 41%, the U.S. PV industry ships 70% of its production overseas. But

with more than two billion of the world's people waiting for the benefits of electricity and with nations continuing to build their economies, we expect this market to grow substantially.

Photovoltaics not only can help meet this growing worldwide demand for electricity, but it can do so without incurring the high economic and environmental costs of installing power lines or burning fossil fuels. The operation of photovoltaic systems produces no emissions—no particulates, carbon dioxide, sulfur dioxide, or nitrogen oxides. Relative to burning coal, in fact, every gigawatt-hour of electricity generated by photovoltaics prevents the emission of up to 1000 tons of carbon dioxide.

Such a promising technology provides ample reason for the National Photovoltaics Program and U.S. industry to continue the cooperation that has established the industry as the market leader and has given the United States the competitive edge in the technology. A continued cooperative program of research, improved manufacturing, and validating system operation promises even greater dividends during the next

*The three-fold promise of photovoltaics is energy security, economic growth, and a clean environment.*



*Recognizing the importance of international markets, DOE supported a project establishing South Africa's first PV manufacturing facility.*

DOE/PIX01994



*A researcher uses a hail tester to determine the ability of a PV module to withstand the impact of hail stones.*

Jim Yost Photography/PIX01820



# The PV Challenge

The challenge before us is to enable photovoltaic technology to fulfill its energy, economic, and environmental promise. By doing so, we will also fulfill our mission of helping PV become a significant part of the U.S. economy.

To meet this challenge, we must advance the status of photovoltaic technology and strengthen the industry. Toward this end, we have established important goals for the next 5 years.

First, we must make photovoltaics more cost-competitive with other forms of electrical generation. Today's PV systems are in fact cost-competitive in many applications, particularly in rural areas. By 1996, the U.S. PV industry had installed a total of 210 megawatts of PV generating capacity worldwide. But we need to reduce the cost of photovoltaics even further to be competitive in a wider range of applications, including some grid-connected uses. Our goal in this regard is for PV to produce electricity at 12 to 20 cents per kilowatt-hour by the year 2000.

Second, we must make photovoltaics as reliable and convenient to

use as the next best alternative for each application. The attractiveness of photovoltaics to consumers includes all aspects of reliability, convenience, and appropriateness for its applications.

The National Photovoltaics Program plan addresses these issues. The cooperative R&D projects described in this plan will increase the reliability of PV components, reduce system costs, and increase system efficiencies. And the systems engineering and applications elements of the program will validate prototype system performance in key applications.

As we meet these goals we will see new markets open up and old ones flourish. In fact, by the year 2000, we expect the U.S. PV industry to have installed between 400 and 600 megawatts cumulative. Such a market will have enabled the U.S. PV industry to more than treble its industrial base—a long stride toward having fulfilled the challenge and the promise of photovoltaic technology and toward having met the mission of the National Photovoltaics Program.

*To help PV meet its promise, we must make the technology more competitive and make PV systems more reliable and efficient.*



*A modular PV system is installed at a remote Navajo home to provide cost-effective electricity.*

Sandia/PIX01559



*Passing the baton to a new generation: college students pose with the PV-powered cars they built and raced from Indianapolis, Indiana, to Golden, Colorado.*



Warren Gretz, NREL/PIX00237

# Meeting the Challenge

To meet the challenge we face in making PV an important part of our energy mix and our economy, the National Photovoltaics Program uses a four-pronged strategy: First, we work in close concert with industry and other stakeholders to develop specific goals that serve as significant milestones on the path to achieving a PV technology competitive with other sources for generating electricity.

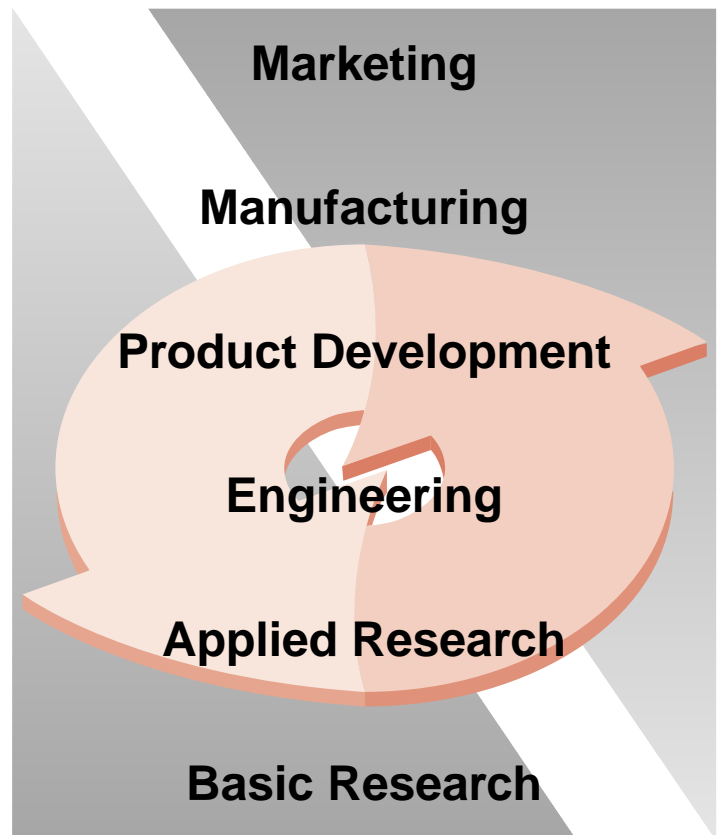
Second, we use an approach known as vertical integration to bring technologies from the concept stage to commercial readiness. Here, the government's role spans most of a long process that includes basic research, applied research, engineering, product development, and manufacturing before it finally results in a new commercial product. The private sector has an increasing role, and the government a decreasing role, as technologies progress through to commercialization, which is entirely a private-sector responsibility.

Third, we augment vertical integration with collaborative projects in which the R&D partners—government, industry, and universities—play important roles. This process promotes “buy-in” from the partners and lends stability and

direction to the program. It allows “mid-course corrections” in the development of a technology. It leverages the expertise, the facilities, and funds of the partners. And it guides concepts according to their final usefulness, which makes the successful development of a technology more likely.

Finally, we deploy and document the performance of prototype systems to validate the technology for specific applications. Key to validating a technology is drawing stakeholders into the process, to inform them of PV's benefits and to gain information about barriers to applications that the program could address and overcome.

The success of this strategy depends on the expertise and contributions of the major partners in the PV



*The PV Program uses a vertically integrated process, with feedback loops all along the development path.*

*The PV Program uses a four-pronged strategy to help make PV an important part of the nation's energy mix and economy: goal development, vertical integration, collaboration with industry and academia, and technology validation.*



Program in the national laboratories, university research groups, and the PV industry.

**T**he Laboratories. Through insights in physics, chemistry, electronics, optics, materials science, and surface science, national laboratory scientists have helped PV become a sophisticated technology.

Engineers and researchers help develop advanced devices and modules, new PV materials and material combinations, more-efficient fabrication and manufacturing processes, better module encapsulants, more sophisticated concentrators and sun-tracking equipment, and automated manufacturing systems. They also help improve PV system designs and refine balance-of-system components, including support structures, power-processing and controls equipment, electronics, monitoring equipment, and storage technologies.

Specialists work with national and international organizations to establish uniform standards and test methods. Rigorous testing ensures that the electrical, mechanical, and safety aspects of PV systems are sound. Analytic studies—including the results of environmental, resource, and market assessments—have an important impact on current and future R&D activities.

The laboratories also serve as incubators for new ideas. Because most companies cannot afford large R&D laboratories, the national laboratories provide long-term, high-risk, high-payoff R&D, which is tantamount to investing in the nation's future—toward clean, sustainable, affordable electricity.

**U**niversities. Universities play a key supporting role in almost every phase of technology development, from basic research to developing new manufacturing processes to deploying and testing prototype systems. The DOE has designated two Centers of Excellence in PV at Georgia Institute of Technology and the Institute of Energy Conversion at the University of Delaware. These and other universities participate in the Thin-Film PV Partnership teams and the Crystalline Silicon Research Cooperative. By tapping into these skills, the PV Program not only leverages the talent and facilities available in the universities, it also helps to

prepare the nation's next generation of scientists and engineers.

The PV Program also conducts programs to attract the interest and talents of the academic community. The University Participation Program for PV Research attracts university research teams to promote basic and applied research ideas in an environment of free-spirited study. The biennial Sunrayce challenges students to design, build, and race PV-powered cars. And an initiative with Historically Black Colleges and Universities (HBCUs) strengthens the research and educational capabilities of HBCUs in photovoltaics.

**I**ndustry. To be relevant and cost-effective, R&D must have the feedback only industry can provide. Through collaborations, consultations, and membership on advisory and planning boards, industry provides the program with direction at all points along a technology's development path.

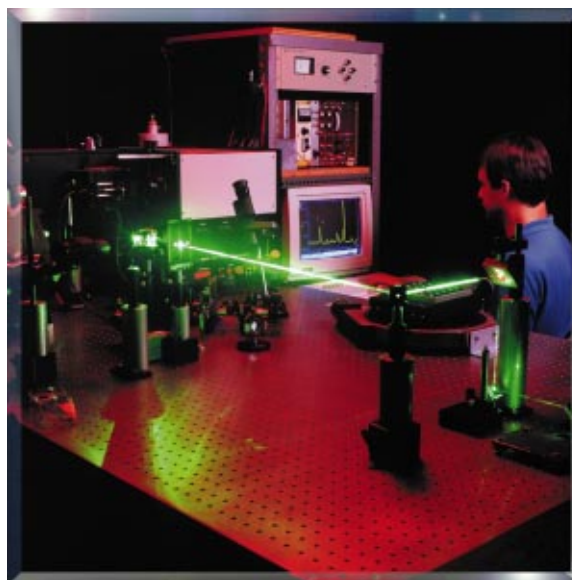
Plus, as an integral member of R&D's efforts, industry often assumes the lead role in the engineering and product development phases of a technology's development cycle. Such is the case, for example, with the PVMaT project. Here, more than 20 companies have joined with DOE in an extremely successful, cost-shared effort to overcome persistent barriers to more-efficient, more-productive manufacturing processes.

Other examples of industry's collaboration with the PV Program include the Thin-Film PV Partnership, a cost-

shared project that is accelerating the efforts of manufacturers to bring thin-film materials to pilot production; the Crystalline Silicon Research Cooperative, which is increasing the efficiency of devices made from crystalline silicon, while decreasing costs and increasing reliability; and



*Solar Energy Research Facility in Laboratory does world-*



*A student researcher at Colorado School of Mines uses Raman scattering to analyze PV materials.*

Jim Yost Photography/PIX01814



Warren Gretz, NREL/PIX01347

*Golden, Colorado. This DOE facility at the National Renewable Energy class research for in-house, industry, and university projects.*

balance-of-system cost-shared R&D, in which DOE and industry seek to manufacture high-quality system components while drastically cutting costs.

These augment and expedite the progress of the PV Program and assist a young but growing industry in producing clean, affordable PV systems.

**P**rogram Goals. The PV Program's cooperative approach has achieved some remarkable results and is well suited to meeting the challenge of the next 5 years. Efficiencies have increased for each technology. New manufacturing approaches have been transferred to industry in record time. We see products entering the market today, like the cadmium telluride module, that were only laboratory curiosities in 1991. And PV systems across the world have proven to be reliable and cost-effective.

One benchmark for measuring technical progress in photovoltaics is efficiency—the percentage of sunlight falling on a PV device that is converted to electricity. Because the resource is free and renewable, PV system efficiency is not comparable to that of other energy technologies; but it must be considered along with cost and ease of manufacture as an indicator of PV's attractiveness and suitability.

Over the next 5 years, the PV Program will focus on

transferring techniques for achieving high laboratory efficiencies to industry, where they can be evaluated for their potential to yield lower-cost production modules.

To be attractive in more applications, PV systems must also last a long time. System lifetimes have doubled since 1991, and manufacturers are providing warranties of up to 20 years on modules. Under this 5-year plan, the program will conduct field measurements and accelerated testing to help extend the useful life of systems to 20 years or more—important for reaching our long-term goal of systems that last at least 30 years.

The price of PV electricity is also an important indicator of the most promising PV applications. We have made steady progress toward our long-term goal of matching the price of electricity generated by fossil fuel or nuclear generating plants. Our mid-term goal of 12 to 20 cents per kilowatt-hour is achievable, but depends on several factors including installed production capacity.

Module manufacturing costs have dropped significantly, especially with the help of the program's PVMaT project. But manufacturing costs must decline even more to help PV compete in wider applications.

Over the next 5 years, PV system costs should decline an additional factor of 2, reflecting continued work on improved PV technologies, module manufacturing, balance-of-system components, and integration of system components into PV products ready for markets.

For PV to become a more important part of our economy, the market must grow and the industry must expand. One measure of the size of the PV industry is cumulative sales of U.S.-made PV systems. We expect cumulative sales to be between 400 and 600 megawatts by the year 2000 as a condition for continued industrial expansion.

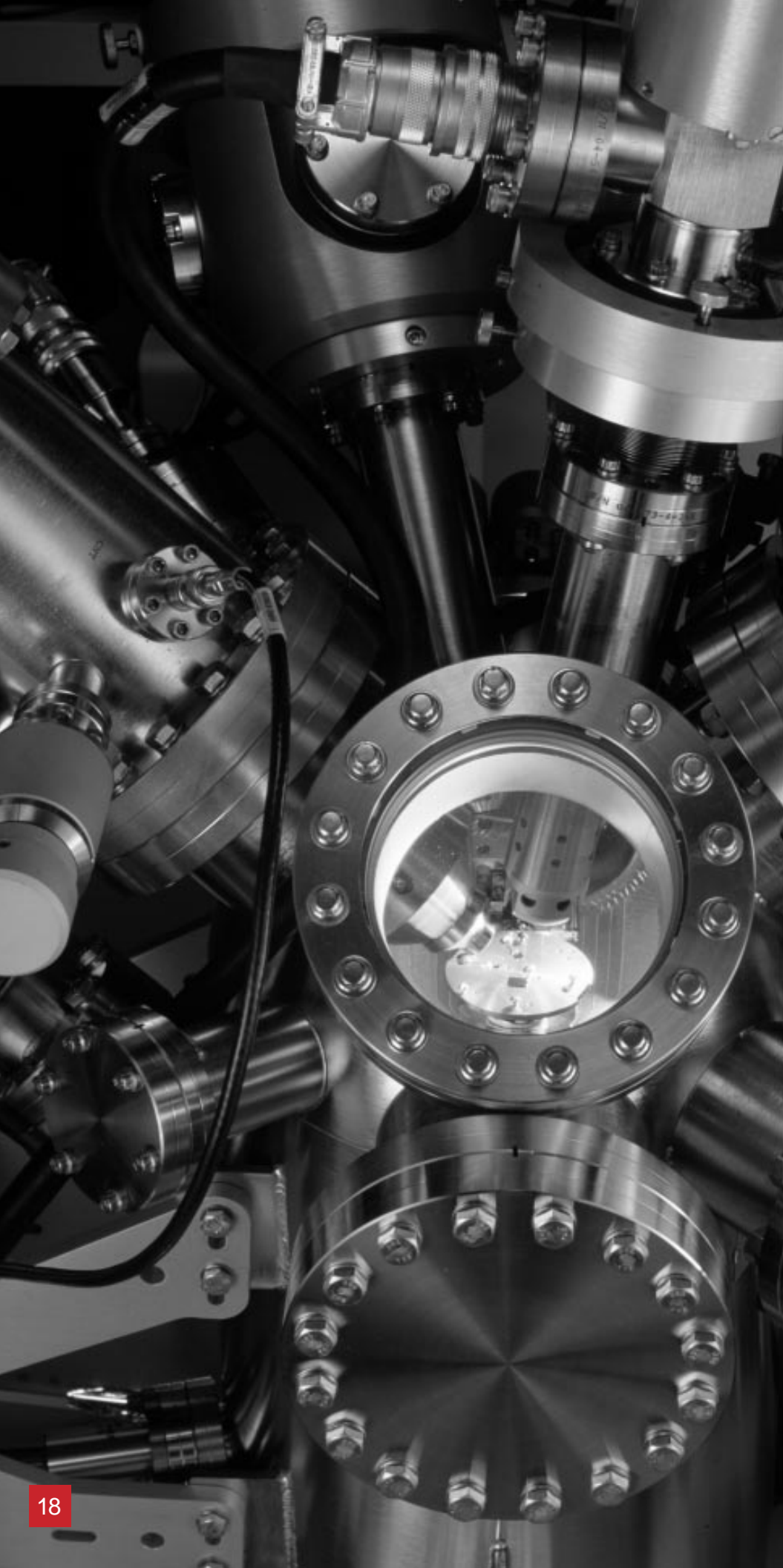
To reach our goals, we must improve our fundamental understanding of materials, processes, and devices; develop new and better low-cost processes and technologies; continue to transfer and scale up laboratory results; reduce module and balance-of-system costs; improve the reliability and durability of components and systems; validate new systems, applications, and technologies; and help overcome market and institutional barriers.



David Patryas Photography/PIX01545

*Golden Photon, Inc., is one of two companies making modules of the new material, cadmium telluride.*





*X-ray photoelectron spectroscopy is used to obtain critical information on chemical bonding and molecular structure of PV materials.*



# Implementing the Program

For photovoltaics to meet its promise as an energy technology, expand its markets worldwide, and make a significant contribution to our nation's energy mix, we must improve the technology so that PV systems will be reliable and durable and will deliver electricity at competitive prices.

Reducing the cost of electricity from PV systems is the chief goal driving our technology R&D program. The program works in three ways to make PV cost-competitive: by making devices more efficient and reliable, by making systems less expensive, and by validating the technology.

To accomplish our aim we have carefully crafted a program that maintains a balance between basic research and technology applications. Each of the three major elements of this program—research and development, technology development, and systems engineering and applications—is guided by technical goals.

*Research and development.* In this area, scientists conduct basic and applied research on promising new materials, processes, devices, and

production techniques. In concert with industry, DOE researchers move ideas from the drawing board to the laboratory bench-scale and prototype development. Key to the success of this program element is the evaluation of new concepts and materials through careful measurements and modeling.

*Technology development.* Translating laboratory innovations in materials, processing, and system operation is the challenge of the technology development portion of the program. Through industry-directed research partnerships, the program advances PV manufacturing technologies, reduces module production costs, increases module performance, improves balance-of-system components, and expands U.S. production capacities.

*Systems engineering and applications.* Under this element, the program measures and documents the performance of photovoltaic systems and disseminates information on PV characteristics. The program also conducts projects that demonstrate the performance and value of PV systems in applications for key markets.

*To advance the technology, the PV Program uses a carefully crafted approach with three balanced and integrated elements—research and development, technology development, and systems engineering and applications. Each element is guided by technical goals.*



*Researchers use Sandia's PV Device Fabrication Laboratory to design, make, and test crystalline silicon solar cells.*

Jim Yost Photography/PIX03525

# Research and Development

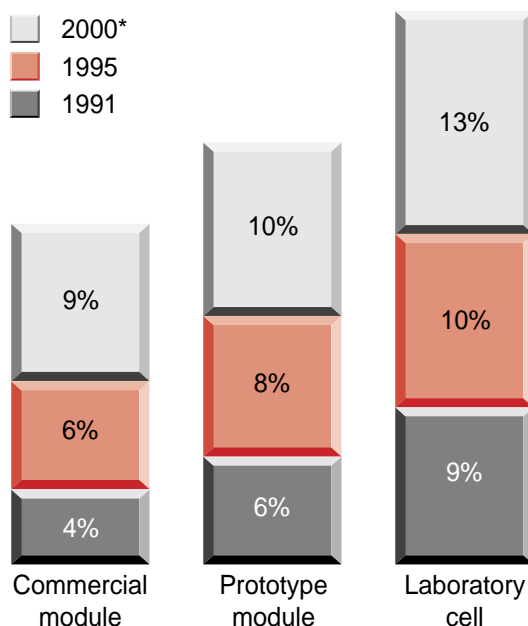
Research and development generates new approaches by turning researchers' ideas into laboratory experiments and prototype devices. In this area, the National Photovoltaics Program conducts R&D in thin films, crystalline silicon, and advanced, high-efficiency concepts.

**T**hin Films. Thin films are a promising path to low-cost photovoltaics, and at least eight U.S. companies are planning or building thin-film photovoltaic manufacturing plants in 1995. This transition to first-time manufacturing is a period of extreme technical and financial risk. Moreover, for thin-film products to reach their low-cost potential, additional research is needed to develop materials and processes yielding devices with higher efficiencies, more uniform performance over the entire surface area of modules, and lower production costs.

But high-technology research is expensive, and the short-term payoff is uncertain for today's PV companies. Therefore, DOE support remains crucial. By combining the talents of scientists performing fundamental research with engineers developing prototype modules, the PV Program can help ensure that a continuous stream of advanced thin-film technology is incorporated into future manufacturing facilities.

In 1995, under the Thin-Film PV Partnership program, DOE awarded major contracts to 9 industrial partners and to about 20 research partners in universities. Through the year 2000, each of the partners will contribute 10% to 50% of the value of these contracts. University researchers, including those at the DOE PV Center of Excellence at the Institute of Energy Conversion at the University of Delaware, play key roles in these efforts. These collaborations will develop prototype products largely based on amorphous silicon, cadmium telluride, copper indium diselenide, and thin-film crystalline silicon technologies.

**Amorphous silicon.** The first thin-film amorphous silicon devices made in 1974 had efficiencies of less than 1%. By 1994 a small, experimental module recorded a stabilized efficiency of 10.2%. Although amorphous silicon materials have lower efficiencies than crystalline silicon,



\*Module goals are for those larger than 4000 cm<sup>2</sup>.

*Progress and goals for efficiencies of the best stable amorphous silicon cells and modules.*

they have the potential to be less expensive to manufacture. Today more than 15% of worldwide PV production uses amorphous silicon technology.

Most products using amorphous silicon are low-power consumer items like solar watches and calculators. Higher-power applications will demand amorphous silicon products with higher stabilized efficiencies so that more energy can be extracted from a given module area. Our research goal during the next 5 years is to raise efficiencies for our best laboratory cells from today's 10% to 13%.

Key to the process is transferring to industry any techniques we perfect in the laboratory. To increase the efficiency of amorphous silicon PV, more than 40 researchers

nationwide are working under the Thin-Film PV Partnership program. These research teams are addressing a dozen issues surrounding the design and fabrication of multi-junction amorphous silicon alloy cells. For example, one team is optimizing back reflectors that direct unused sunlight back up through the thin layers of a multijunction cell. Another team is modeling the effects of using various



*Hot-wire deposition promises to improve the efficiency and stability of amorphous silicon devices.*

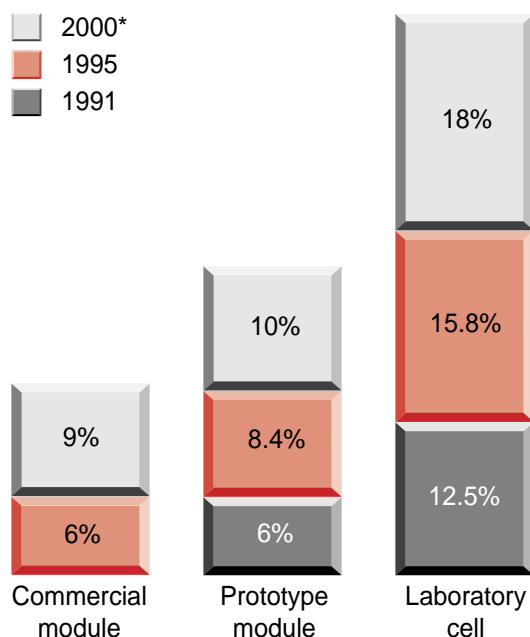
Jim Yost Photography/PIX01813

combinations of alloys and thicknesses in the multijunction layers and is investigating new structures. Other teams are improving the output from the individual component cells in the multijunction device.

In addition, researchers are developing ways to process amorphous silicon material that improve its stabilized efficiency. The most-promising approach to date is hot-wire deposition. The extremely hot (2000°C) temperatures of the wire cause dissociation of the feed gases and deposition of the active radicals at rates up to 10 times higher than the glow-discharge method used in industry today. The resulting material contains less hydrogen, the agent suspected as the cause of amorphous silicon's instability. Tests in early 1995 indicated that material created with the hot-wire method is much more stable than conventional amorphous silicon; later tests showed that efficiency can approach the state of the art. Future work will investigate the viability of this alternative approach to replace existing processes.

By 2000, working with industry on device design and material deposition techniques, our goal is to improve the stabilized efficiency of laboratory amorphous silicon devices. Moreover, our research results can be transferred to the production line because there is a mature manufacturing base for amorphous silicon. The progress of amorphous silicon, from technical conception through manufacturing maturity and ongoing technical progress, has been a triumph of past DOE partnerships with industry. We expect the future to yield the fruits of such a combined approach.

**Cadmium telluride.** The National Photovoltaics Program is exploring cadmium telluride because the techniques used to manufacture devices from this material—including electrodeposition, spraying, and high-rate evaporation—are potentially very low-cost. It also promises high efficiencies—small laboratory devices have reached nearly 16%, although commercial module efficiencies hover around 6%. Two U.S. companies are preparing to bring prototype products to market that should compete with established products made from crystalline silicon.



\*Module goals are for those larger than 4000 cm<sup>2</sup>.

*Progress and goals for efficiencies of the best cadmium telluride cells and modules.*



Jim Yost Photography/PIX01504

*Scientists use close-spaced sublimation as one way to make and study high-efficiency cadmium telluride devices.*

Our goal is to convert the high cell efficiencies we have achieved in the laboratory into more-efficient production modules.

Increasing module efficiencies is challenging because, despite our progress, our fundamental understanding of the properties of cadmium telluride is limited. For example, some modules have exhibited stable performance for 6 years outdoors, while others have shown significant declines in efficiency in a matter of days. The mechanisms of this uncertain stability have yet to be fully characterized.

In addition, researchers often achieve high cell efficiencies using approaches that are far from being available to manufacturers. For example, high-quality 7059 glass is used for the best cells, but it is too expensive to be used in production (where soda lime glass is used). The high efficiencies of small-area cells are due in part to the deposition of very thin layers of cadmium sulfide. No one has learned how to achieve such a thin layer in a module-scale device; a thicker layer reduces efficiency by about 25%.

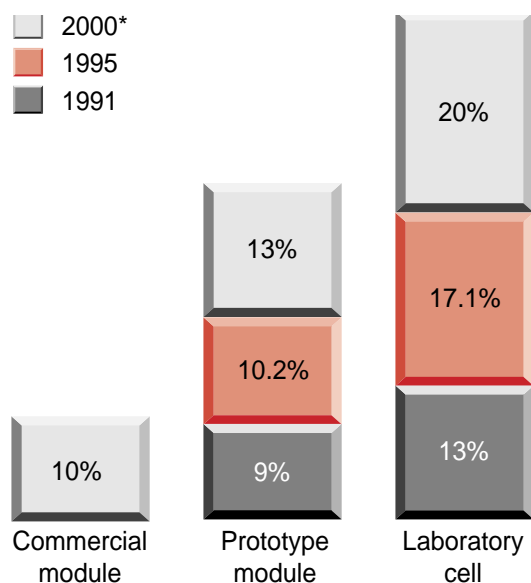


To meet challenges like these, 25 researchers nationwide are working in teams under the Thin-Film PV Partnership program. One team is studying instability in cadmium telluride materials and devices to learn how to design and build stable modules. Another team is working to adapt laboratory cell-fabrication techniques for large-scale production. These efforts should help the photovoltaic R&D community realize the potential of high-efficiency cadmium telluride cells for high-efficiency power modules.

**Copper indium diselenide.** In 1995, researchers pushed the efficiency for devices based on copper indium diselenide to 17.1%, the highest efficiency recorded for any thin-film cell. A prototype power module has been measured at 10.2%. And copper indium diselenide is the only thin-film material with many years of outdoor exposure that shows no deterioration in performance. Yet, in 1995 there were no commercial products based on this material and its alloys.

Copper indium diselenide is not yet commercial because significant further research is needed to understand the manufacturing processes. Fabricating high-quality films requires making a copper-rich layer and a copper-poor surface layer to form a junction with other alloys. Researchers in this technology have difficulty avoiding defects that prevent the formation of uniform layers. Using proper temperatures and correctly timing the process steps are critical to achieving quality results.

To reach the goal of manufacturing commercial copper indium diselenide products, 40 researchers nationwide are working to devise simpler, more-effective fabrication methods as part of the Thin-Film PV Partnership program. Basic to this activity is a better understanding of the chemical and physical properties of this material. Researchers in the program have learned much about how the various elements and compounds combine to form quality copper indium diselenide. And the more we understand about temperature, phase-change reactions, and which steps can precede others, the better we can simplify the process for adaptation to industry.



\*Module goals are for those larger than 4000 cm<sup>2</sup>.

*Progress and goals for efficiencies of the best copper indium diselenide cells and modules.*

**Thin-layer crystalline silicon.** Although crystalline silicon absorbs sunlight about 10 to 100 times less effectively than other thin films, thin-layer crystalline silicon cells can be more efficient than those made of other thin-film materials if properly constructed to trap light. The advantage to using silicon is that it is familiar and well-studied.

So far, researchers have deposited relatively thick layers of crystalline silicon on low-cost substrates. Future work will focus on thinning the material to less than 50 micrometers, while developing optimal substrate, light-trapping, and interconnection schemes.

**C**rystalline Silicon. Crystalline silicon is likely to continue to

dominate PV markets at least through the year 2000. With its relatively high efficiency, stability, competitive cost, and proven track record, it plays a dominant role in both domestic and international markets. In 1994, modules made of crystalline and multicrystalline silicon accounted for about 95% of all the modules sold by U.S. PV manufacturers.

Today's crystalline silicon devices are more efficient than ever before. Laboratory cells made from single-crystal silicon have measured efficiencies as high as 24%.



Jim Yost Photography/PIX03524

*The program has developed a new approach for making high-efficiency copper indium diselenide devices.*



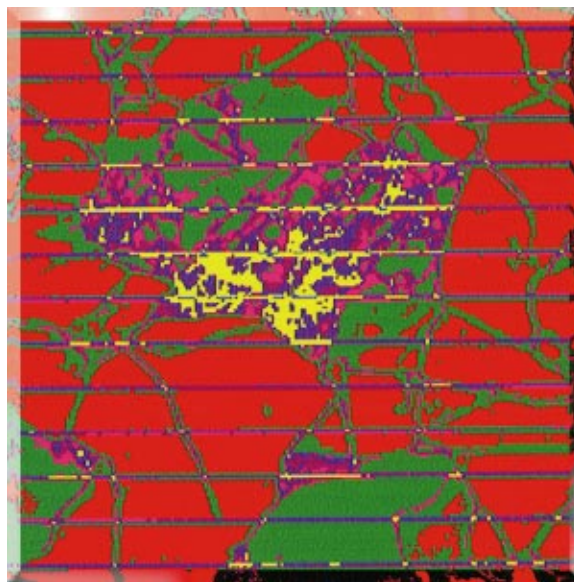
Research on manufacturing improvements has pushed the efficiencies of multicrystalline devices to nearly 18% for laboratory cells and over 15% for prototype modules. Commercial modules of 14% efficiency are made in production.

Over the next 5 years, our research will focus on reducing the cost of electricity from commercial flat-plate modules by increasing the efficiency of low-cost materials. The low-cost silicon used by industry has lower efficiencies than the pure silicon used in the laboratory. Defects and impurities in the material interfere with photo-electric conversion and the transmission of electrons within the cells and modules. Armed with an understanding of the microscopic and atomic processes at work, researchers are working with industry to devise techniques of material growth and device processing that circumvent or compensate for these impurities and defects.

We are also working with industry to push the efficiency limits of pure silicon-based devices. The emitter-wrap-through cell, for example, employs both positive and negative electrical contacts on the cell's back surface. This technology could reduce manufacturing costs and prevent current losses due to shading by grid lines.

Increasing the efficiency of crystalline materials through improved processing is a major goal of the PV Program's Crystalline Silicon Research Cooperative, whose partners include six U.S. manufacturers and the national laboratories. Sandia and NREL researchers characterize materials prepared by industry to help them assess changes in manufacturing processes. University researchers, including those at the DOE PV Center of Excellence at Georgia Institute of Technology, also play a key role in these efforts.

**A**dvanced, High-Efficiency Concepts. The National Photo-voltaics Program also supports emerging advanced, high-efficiency technologies for specialized markets, including concentrator systems. These technologies include gallium arsenide, with a measured single-junction efficiency greater than 25% at 1-sun and nearly 28% under concentrated



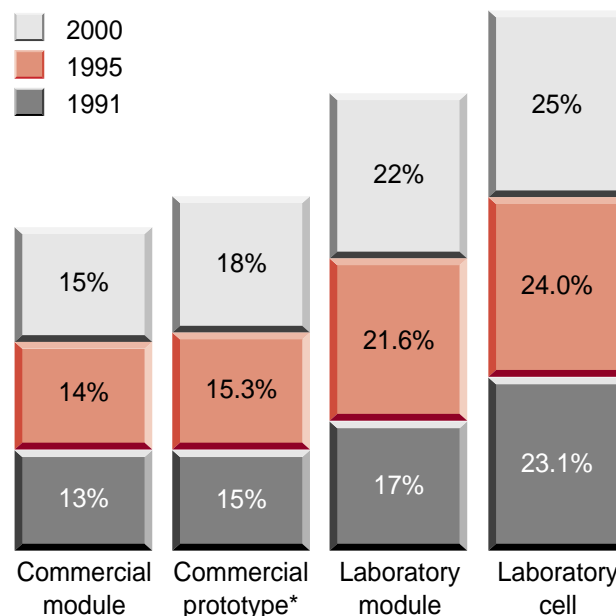
*A commercialized NREL invention uses laser beam-induced-current maps to analyze silicon materials.*

Bhushan Sopori, NREL/PIX03521

sunlight, and multijunction cells based on gallium arsenide and related III-V alloys, with conversion efficiencies greater than 30%. We expect to exceed 32% efficiency using these devices in concentrator systems. Industry efforts in this area are driven by space markets today.

High-efficiency device research improves our understanding of the electronic processes in PV devices so that we can better control the factors that cause losses in efficiency. Improvements in basic science resulting from this work are often applicable to all other technology areas in ways that cannot be anticipated. For example, these materials may result in very high efficiency thin films (greater than

25%). Continued support for cutting-edge science through universities, research centers, national laboratories, and industry is an important aspect of the PV Program.



\* Figures are for prototype modules on commercial material.

*Progress and goals for efficiencies of the best single-crystal silicon cells and modules.*

# Technology Development

U.S. industry leads the world in driving down the cost of PV systems. The program supports industry's attempt to decrease costs by exploring manufacturing technology to reduce production costs; by increasing the performance and reliability of modules; and by boosting the reliability of BOS components while reducing their cost.

**M**anufacturing Technology. In 1991 DOE began PVMaT—a 5-year, \$100 million cost-shared initiative—to reduce module costs and boost production capacity. The first 8 companies to receive PVMaT subcontracts reduced module manufacturing costs by 50% or more and are expected to carve another factor of 2 from manufacturing costs by 1997. Participating companies also increased their manufacturing capacity from about 12 megawatts per year to about 35 megawatts. Three companies successfully introduced new product lines with lower costs and improved performance.

Further cost reductions are necessary to expand PV markets, so the next 5 years of R&D are vitally important to the industry. The program intends to achieve cost reductions by trimming manufacturing costs, modifying laboratory techniques for production, optimizing PV products, and testing product performance.

**Reducing manufacturing costs.** Manufacturing costs depend on many factors of production, and research is under way to optimize several. An important factor is throughput—the rate at which PV materials or devices are passed through the processes of material deposition, preparation, encapsulation, and connection to electrical components. Examples of measures taken under PVMaT to increase throughput include automating the assembly process, reducing the number of steps in a process, and moving from batch processing to continuous processing.

Another important cost factor involves material. We are exploring ways to get more from relatively costly materials through thinner device designs and more-precise fabrication methods with less waste.

**Modifying laboratory techniques for production.** The high-efficiency materials developed in the R&D program



*As a PVMaT participant, Spire Corporation has developed an automated module assembly unit.*

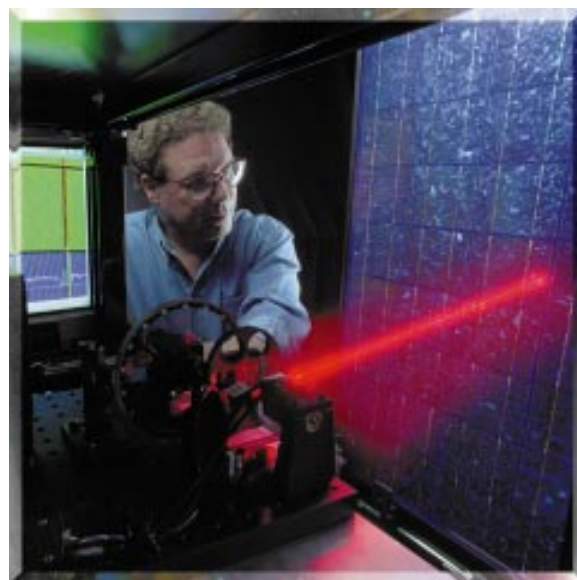
Spire Corporation/PIX03539

must eventually be manufactured in quantity by the PV industry. Therefore, the PV Program develops and tests ways to control parameters like temperature and pressure for processes on large batches of material. It also devises alternatives to costly laboratory techniques, which are often not possible to duplicate in a manufacturing environment. And, it explores ways to ensure the manufacturability of promising materials,

whose composition changes when manufactured in quantity.

**Optimizing PV products.** While continuing work on PV processes and materials, PVMaT also addresses refinements of the entire PV product. Manufacturers and systems developers conduct R&D to integrate PV system components for optimal performance, reliability, and lifetime. They simplify systems and select the most durable components. And they work to improve BOS components such as inverters, batteries, and control systems.

**Testing product performance.** Documenting what works and what does not is crucial for improving PV products and processes. Typically, therefore, when manufac-



Pat Corkery/PIX01029

*Researcher uses laser scanner to identify causes of uneven performance in a module.*

turers produce a new or prototype product, they send the product to NREL or Sandia where researchers verify the product's performance, document the results, and send the information back to the manufacturers.

**M**odule Development. Cooperative research in materials and devices flows into module development and testing. Issues of module development, such as incorporating new cell designs into modules, are addressed in several parts of the program. Manufacturing technology developments and module test results contribute to refinements in module designs.

Issues arise among manufacturers that cooperative research can readily address. For example, certain encapsulants used to seal PV modules discolored after several years in the field. The program sponsored work to measure the degree of discoloration and its effects on performance. Plus, researchers developed more durable encapsulants.

As new technologies and manufacturing techniques are tried, researchers address issues of module performance and durability by testing thin-film modules, developing accelerated tests to predict factors affecting 30-year outdoor life of modules, measuring electrical performance characteristics, and analyzing failures. Results are quickly transferred back to industry.

**B**alance-of-System Components. In addition to PV cells and modules, all PV systems have other components that help to convert, deliver, and store electricity. Today, BOS components represent half the cost of a PV system, but they are responsible for 99% of system repair problems. Plus, about 15% of the electricity generated by PV modules is lost during conversion and transmission through BOS components.

Balance-of-system components include charge controllers, batteries, control systems, mounting hardware, tracking systems, wiring, and power-conditioning hardware such as inverters. Failures of inverters, which convert the direct current (dc) from PV modules to alternating current (ac), are the number-one cause of PV system problems. Recent tests at



*A technician checks a state-of-the-art 300-kW inverter, which converts direct current into alternating current.*

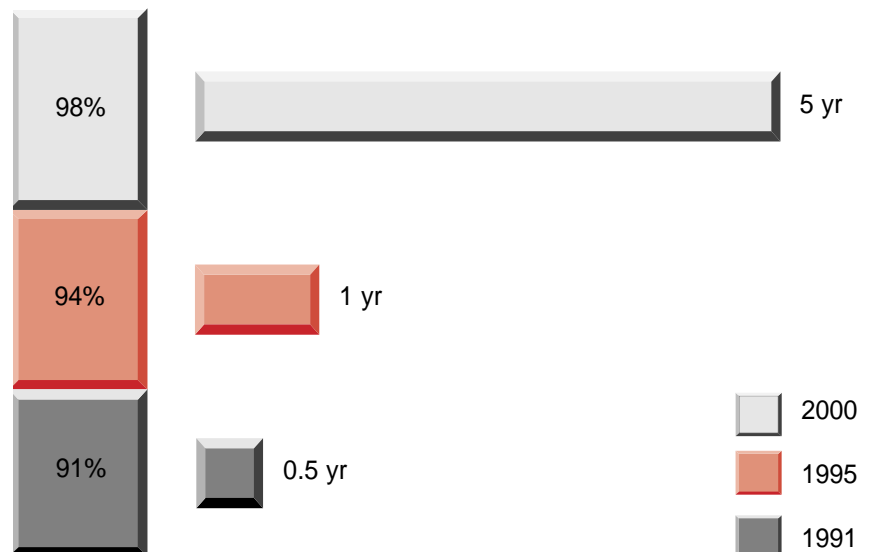
Jim Yost Photography/PIX01821

Sandia's Power Processing Laboratory have shown that most of today's inverters exceed accepted levels of acoustic noise and radio-frequency interference (RFI). Cooperative R&D contracts will support the development of quieter, more reliable inverters that can be mass-produced for the PV industry. Also scheduled for tests and improvements are trackers, control units, charge controllers, and batteries.

We expect to bring down the cost of BOS components and improve their performance. Many of today's systems are one-of-a-kind; they incur very high costs for design and installation, which should be reduced when the systems are

mass-produced. And few designs for mechanical or electronic BOS components have been optimized for photovoltaics. So, their cost and performance should improve as system designs improve. Rapid advances in power electronics for a variety of applications will also improve the performance and reduce the cost of entire PV systems.

Our goals are to keep the cost of BOS components to less than 50% of the total PV system cost, improve their reliability, and increase their efficiency. For inverters, we intend to increase their efficiency to 98% and the mean time between failures to at least 5 years.



*Progress and goals for inverters: efficiency (%) and mean time between failure (yr).*



# Systems Engineering and Applications

Building a strong industry and stimulating a healthy market is the ultimate aim of the PV Program.

Toward this goal, the program works with industry to test, evaluate, and improve its systems and works with end users, agencies, and industry to deploy and validate cost-effective PV applications for key markets.



*The Outdoor Test Facility at NREL is used to evaluate prototype, precommercial, and commercial modules.*

Warren Gretz, NREL/PIX03540

**S**ystems Engineering. The program works with industry to test and validate the performance of emerging technologies and to develop codes and standards.

*Testing and validation.* The program makes its facilities available to industry to evaluate the material, mechanical, electrical, and safety characteristics of PV cells, modules, BOS components, and complete systems.

By providing U.S. PV manufacturers with laboratory assistance in the form of tests, measurements, and characterizations, program scientists and engineers can help these typically small companies accelerate product improvements.

By testing and evaluating prototype and precommercial modules, the program helps industry understand and improve the performance, reliability, and operational characteristics of its products. Toward this end, the program recently installed a new outdoor test facility at NREL to correlate the measured solar resource, air temperature, humidity, and wind with the electrical performance of modules.

The laboratories and their contractors have also organized an extensive network to evaluate the field performance of systems, which is critical for understanding and improving hardware performance and reliability.

*Codes and standards.* To be accepted in potential markets, PV systems must conform to national and international standards of safety and reliability such as Underwriters Laboratories (UL) and the National Electrical Code (NEC). Many of these codes, however, do not currently address PV systems directly. The program works closely with industry in standards groups to ensure that there are appropriate requirements for commercial PV systems. The program personnel also work with manufacturers to help get their products approved by such organizations.

Many potential consumers are also interested in standard reporting of expected energy production, similar

to the annual-energy-use stickers now on major appliances. The program contributes its facilities and expertise to develop such standard reporting methods.

**A**pplications. The program also works with industry to validate the performance of prototype PV technologies in specific domestic and international applications.

*Domestic applications.* Through PV Program-sponsored projects for domestic applications, manufacturers gain experience supplying potential markets, buyers gain experience with PV systems, and researchers obtain technical feedback to improve products and processes. These projects validate PV systems for grid support, demand-side management, grid-connected applications, and remote applications.

*Utility PhotoVoltaic Group.* This group was formed in 1992 to accelerate utility acceptance of PV in grid-tied applications and cost-effective small-scale applications. By 1995, the group had 89 member utilities that produce almost half of the electricity consumed in the United States. The program will continue to provide financial and technical support to the group to test PV systems in domestic utility applications.

*Photovoltaics for Utility-Scale Applications (PVUSA).* This project, which installed the world's first transmission and distribution system powered by PV, tests and validates utility-scale applications. The program will continue to support the project, including the PVUSA test site in California and additional studies for utility applications.

*Building Opportunities in the United States for Photovoltaics (PV:BONUS).* Buildings use about two-thirds of the electricity generated in the United States. There is also a great deal of space on the roofs and walls of these buildings that could support PV generation capacity. According to one study, between 270 and 320 megawatts of PV would be cost-effective on buildings at a system cost of \$3000 per kilowatt. Incorporating PV into buildings at the design





Sacramento Municipal Utility District/PIX01026

*The Sacramento Municipal Utility District installed this 210-kW system at its Hedge Substation.*

and construction stage lowers costs and increases the value of the electricity generated.

Through PV:BONUS, the PV Program helps teams from the building industry develop prototype PV products that could replace conventional windows, skylights, and walls while generating electricity. Because incorporating PV into building materials is technically complex, the program also helps industry develop the technology for PV roofing material, PV modular homes, an ac PV module, and peak-shaving PV that utilities can dispatch.

**Photovoltaics for Federal Agency Applications.** Federal agencies have been directed to reduce their energy consumption and their use of fossil fuels, opening a large potential market for photovoltaics. The DoD/DOE/EPA Strategic Environmental Research and Development Program has estimated that more than 3000 megawatts of PV—mostly grid-connected systems larger than 500 kilowatts—could be justified for military uses today. Other agencies likely to install photovoltaic systems include the National Park Service, Bureau of Land Management, U.S. Fish

and Wildlife Service, U.S. Coast Guard, U.S. Forest Service, Federal Aviation Administration, U.S. Army Corps of Engineers, the Environmental Protection Agency (EPA), and DOE itself.

The National Photovoltaics Program supports federal agencies interested in deploying PV systems. Federal government procurement procedures require information and certification of PV systems. The PV Program works on performance testing and certification projects to provide uniform, long-term performance data.

**International applications.** Most of this fast-growing market for PV is made up of people who lack a reliable source of electricity—about 40% of the world's population. Often, these people require only small amounts of power for such applications as indoor lighting or pumping water, applications for which PV electricity is often the least expensive and most reliable power alternative.

To take advantage of this huge market, we must find ways to finance the purchase of PV systems and establish reliable installation and maintenance services. In-country structures for financing, installation, and maintenance usually have to be worked out country by country. International lending agencies require assurances of a technology's performance before they grant a loan.

Over the next 5 years, the PV Program will address these issues by helping to conduct demonstrations and to secure development loans from lending institutions. Photovoltaic systems in Mexico and Brazil are already demonstrating the benefits of small and village systems for rural areas. Additional pilot projects are planned for India, China, South Africa, Russia, and other developing countries.



Roger Taylor, NREL/PIX01270

*In Cacimbas, Ceará, Brazil, 50-watt PV systems provide homes with energy for fluorescent lights.*

*Through legislation and budget appropriation, the U.S. Congress helps determine the direction of the National Photovoltaics Program.*

# Guiding the Effort

One of the hallmarks of the National Photovoltaics Program is diligent, responsive management.

In this section of the program plan, we briefly describe how the program's policies are established, how the National Photovoltaics Program is organized, how R&D goals and strategies are determined, and how program funds are distributed among the participants. We also briefly describe the programmatic functions of the two primary national laboratories involved in the National Photovoltaics Program: the National Renewable Energy Laboratory and Sandia National Laboratories.

**E**stablishing Policies. In the Executive branch of the federal government, the Secretary of Energy develops the overarching federal energy policies that guide the National Photovoltaics Program. These policies reflect the recommendations of the Chief Executive and various national energy advisory boards; the policy directives of the Secretary of Energy ensure that broad national goals for energy R&D and technology transfer are met.

Congress helps to determine the activities and direction of the program, through legislation and budget appropriations. And technical review committees made up of experts from the private sector advise program managers on the appropriate scope, objectives, and activities of the program.

Managers of the PV Program then develop operating plans that respond to federal policies, Congress, and the program's constituents. They ensure that the budget allocations, direction, and individual elements of the program meet the objectives of its framers and stay on target.

**O**rganizing the National Program. In the Department of Energy, the Office of Energy Efficiency and Renewable Energy in Washington, D.C., oversees the PV Program through its Photovoltaics Division. In turn, the Photovoltaics Division carries out the bulk of programmatic work through two primary research centers: the National Renewable Energy Laboratory in Golden, Colorado, and Sandia National Laboratories in Albuquerque, New Mexico. Brookhaven

*The Department of Energy establishes policies, organizes the program, distributes funds, and, with input from advisory boards and program participants, determines R&D goals and strategies.*

*At DOE headquarters, program managers develop plans that respond to federal policies, Congress, and program constituents.*

National Laboratory in Upton, New York, supports the program in environmental, safety, and health research.

Staff at these research centers are responsible for the day-to-day management of program activities and for meeting its technical goals. They manage and carry out large R&D projects, in-house research projects, and subcontracted work in areas assigned by the director of the Photovoltaics Division in Washington.

In addition, staff at DOE's Golden Field Office in Colorado and elsewhere administer contracts with the private sector in certain program areas. Integration of activities at NREL, Sandia, and DOE's Golden Field Office is achieved through a combined annual operating plan containing regular meetings and detailed plans.

The National Photovoltaics Program awards most of its federal funds to industry, universities, and other research centers around the country. These awards are made chiefly through competitive procurements.

**S**etting Strategies and Schedules. Following the guidelines set by the Assistant Secretary for Renewable Energy and Energy Efficiency and the Photovoltaics Division in Washington, program managers at the research centers and field offices determine specific R&D strategies in concert with other PV Program members. After analyzing the findings of previous program review meetings, program staff work with staff in Washington and the field offices to establish technical goals, strategies, and milestone schedules for the next 5-year period.

Program review meetings are critically important for evaluating progress and determining future activities to meet program goals. Key staff members in government, industry, and universities attend these reviews and contribute to the strategic planning process.

Members of the PV Program have established broad R&D goals for fiscal years (FYs) 1996 to 2000 under three



*To best achieve program goals, PV program managers distribute funding among the program elements.*

Jim Yost Photography/PIX03526

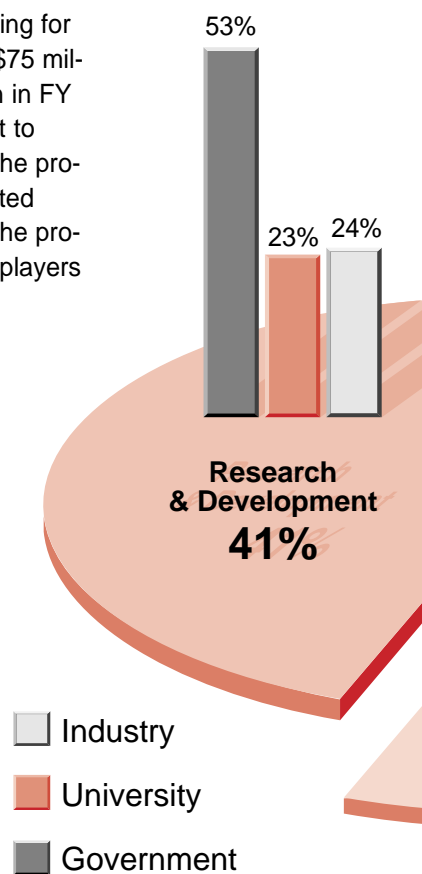
major program elements: research and development, technology development, and systems engineering and applications. These goals are shown in the table on the inside back cover of this plan. Industry milestones shown in the table depend on private-sector investments.

Program managers divide these broad, 5-year goals into various targeted R&D projects with specific multiyear and annual milestones. Projects that are not carried out in the national laboratories are done through subcontracts managed at NREL, Sandia, or DOE field offices. Progress toward meeting project milestones and program

goals is routinely reported to the program's directors in the Photovoltaics Division in Washington.

**F**unding the Program. Funding for the PV Program amounted to \$75 million in FY 1994 and \$84 million in FY 1995. With an eye on how best to achieve the strategic goals of the program, this funding was distributed among the major elements of the program and among the program players (government, industry, and universities).

Overall, federal contract support for the PV Program has been more than matched by industry. In addition to cost-sharing contracts, typically cost-shared 50-50, the private sector's investment in developing manufacturing facilities exceeds the overall government support by a factor of 2 or more. Industry has



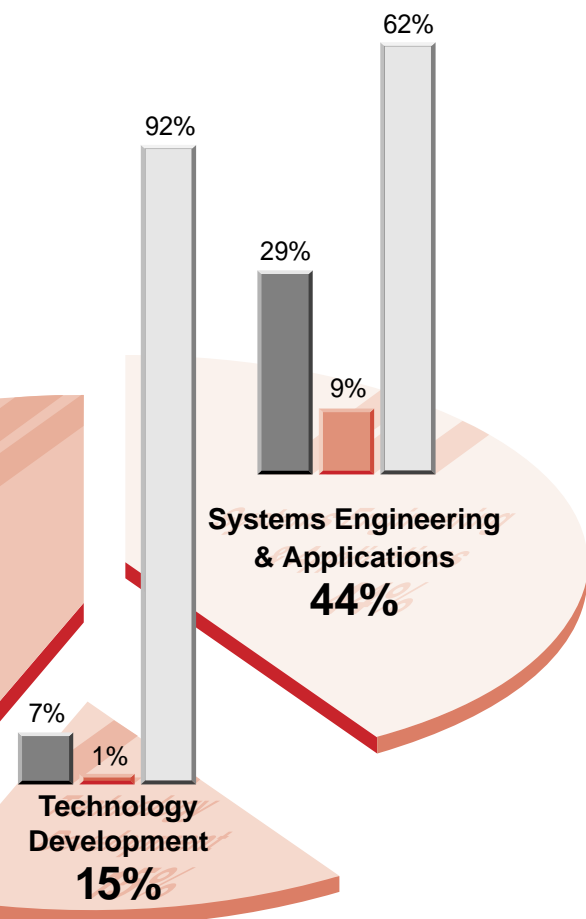
National Photovoltaics



generated new jobs in nearly every state in the country, and nearly 100 companies participate directly in the program. Currently, more than 70% of U.S. PV products are exported, which is contributing to a more favorable balance of trade for the United States.

However, other investments and new financing are also crucial to the success of the U.S. PV industry. Large national and multinational projects in particular require the participation of international development and financing organizations, as well as the DOE PV Program.

Future program activities will continue, through basic research projects and carefully planned R&D collaborations, to find new and better ways to convert sunlight to electricity and to assist promising young industries in becoming self-sustaining. The promise of photovoltaics will be fulfilled when this versatile, operationally simple technology is fully able to meet a significant share of the needs of our nation—and the entire world—for clean, affordable electricity.



## National Laboratories

**S**andia National Laboratories. Located in Albuquerque, New Mexico, Sandia is a multi-program R&D laboratory of the U.S. Department of Energy. Under the National Photovoltaics Program, Sandia has principal responsibility for research in crystalline silicon cells, the development of concentrating collectors, and the development of systems and balance-of-system technologies. The emphasis in each is to work with industry and users to accelerate the development and acceptance of PV technologies.

The Photovoltaic Device Fabrication Laboratory, the Design Assistance Center, and indoor and outdoor measurement and evaluation facilities support industry in measuring, evaluating, and analyzing PV cells, modules, and systems.

**N**ational Renewable Energy Laboratory (NREL). Located in Golden, Colorado, NREL was established by Congress in 1977 as the nation's primary center for renewable energy research and development. NREL manages PV-related R&D activities that include cost-shared, multiyear government-industry partnerships, national team-research efforts, and technology initiatives.

Scientists at NREL also support the PV Program with device measurements, cell modeling and fabrication, and the characterization of both materials and devices using advanced measurement equipment and techniques.

Researchers conduct simulated and actual outdoor tests on cells, modules, and arrays for industry and universities. They also compile solar radiation data to help create computer models—critically important to designers and manufacturers of solar systems—and provide instrument calibrations in accordance with national and international standards.

		1996
Research and Development	Thin Films	
	Crystalline Silicon	19%-efficient large-area cell on commercial material
	Concentrators	
	Fundamental Research	Assess hot-wire deposition of amorphous silicon
Technology Development	Manufacturing Technology	Assess module cost and manufacturing capacity data from PVMaT contractors
	Module Development	Critically assess ethylene vinyl acetate
	BOS Components	Assist grid-tied inverter industry with UL/ETL listing and RFI mitigation Validate viability of PV/hybrid power systems
	PV Industry	Commercial facility for laboratory and module certification
Systems Engineering and Applications	Systems Engineering	Assess outdoor performance of advanced PV modules and arrays
	Domestic Applications	Assess PV-buildings market potential and needs Assess PV commercialization in utility markets
	International Applications	Implement pilot projects in India, China, South Africa, and Russia

# PV Program Technical Areas and

1997	1998
Assess teamed research activities in Thin-Film PV Partnership program	18%-efficient, stable thin-film solar cell
	25%-efficient float-zone silicon solar cell
Assess university PV Centers-of-Excellence strategy	Assess Historically Black Colleges and Universities programs
Assess module cost and manufacturing capacity data from PVMaT contractors	Assess PVMaT contributions and future directions
Publish IEEE all-encompassing qualification test procedures	
Achieve design lifetimes from batteries in PV systems and provide industry-oriented, battery-use guide	
	Commercial crystalline silicon module, >15% efficient Commercial thin-film module, >8% efficient
Assess the needs of standards activities for modules, batteries, and inverters	
Validate system applications for federal, state, and municipal markets	Document PV-building systems
Document system field performance in Brazil and Mexico	Assist expansion of Brazil and Mexico programs through multilateral loans



# Milestones

1999	2000
13%-efficient, stable amorphous silicon solar cell	13%-efficient prototype module
	18%-efficient prototype module on commercial material
32%-efficient monolithic multijunction solar cell	
Assess low-cost processes for deposition of copper indium diselenide	
	Assess PV industry manufacturing status and needs
	Demonstrate low-cost, stable module encapsulant compatible with 30-year life
Develop streamlined system specifications through standardized tests for balance-of-system components	Validate grid-tied inverters with mean time between failure of greater than 5 years available for less than 40 cents per watt
	U.S. manufacturing capacity >120 megawatts U.S. world market share >45% Commercial thin-film module, >10% efficient
	Demonstrate commercial systems compatible with 30-year life
	Document systems field performance for domestic markets
Document system field performance in India and China	Assist expansion of India, China, South Africa, and Russia programs through multilateral loans

**Front cover:** Clockwise from left: a 210-kilowatt PV system at a Sacramento Municipal Utility District substation; a researcher analyzes the output current of a PV module; 50-watt PV systems on homes in Cacimbas, Ceará, Brazil; and ASE Americas' facility for making multicrystalline silicon wafers.

**Inside front cover:** Workmen install PV modules on the Natatorium, the main swimming facility for the 1996 Summer Olympic games in Atlanta, Georgia. The modules will provide 340 kilowatts of dc electric power, the world's largest building-integrated, roof-top PV system. (Craig Miller Productions/PIX03500).

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